SHOCK WAVE STRUCTURE IN RECOMBINING LOW-DENSITY PLASMAS*

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The spatial distribution of the electron properties in the neighborhood of a shock wave in a partially ionized gas is much different than the distribution of the heavy particles.[1] The study of the distribution of the electron properties is made difficult in many laboratory plasma flows because the scale length for the shock wave is often larger than the experimental apparatus and the electrons are never in thermal equilibrium with the heavy particles. Under some conditions of these nonequilibrium flows, it is possible that the electron temperature distribution is governed principally by thermal diffusion. This scale length may be smaller than the experimental apparatus and permits identification and interpretation of some of the effects of a heavy particle shock wave on the electron gas.

Electron density and temperature distributions were measured in front of a flat disc in cesium-seeded gas plasma in an effort to examine the case where thermal diffusion is a dominant feature in a nonequilibrium plasma flow. The region of interest extended several body diameters upstream of the disc and through the heavy particle shock. The experiment was carried out at a Mach number of 5.1 with a free stream number density of electrons from $4(10^{11})/cm^3$ to $1.6(10^{12})/cm^3$ and with an electron temperature between .058 ev to .12 ev. The background pressure of the neutral argon gas was set at a fixed level of 100μHg, which together with the ionized cesium represents a degree of ionization from 10^{-4} to $4(10^{-4})$. The plasma was recombining under these conditions even through the shock wave and was quite luminous. At these low energies,

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recombination radiation measurements of the diffuse series limit of cesium proved most accurate (estimated error of $\pm$ 4%) in measuring the electron temperature. Lack of local thermodynamic equilibrium prevented use of the more intense line spectra for this purpose. Figure 1 shows typical results of the electron temperature measurements vs distance. In general the electron temperature upstream of the shock wave was considerably higher than the calculated value of 250°K (.021 ev) for the heavy particles (T_g). It was also considerably lower than the temperature of the atoms behind the shock, a fact of considerable importance in understanding the experiment. Approaching the atom shock wave from upstream, the electron temperature gradually increased and then underwent a sharp increase across the shock with no detectable change thereafter. At different plasma conditions the magnitude of the changes and electron temperature levels were of course different, but the trends remained the same.

Free molecule Langmuir probes showed very little change in ion or electron density ahead of the shock wave, in close accordance with the spectroscopic observations. To measure the absolute density level of the ionized species an electrostatic probe was placed at the stagnation point of the disc model and suitably biased to collect only ions. Complete saturation permitted easy identification of the ion current. The ion current was interpreted to give free stream ion density (equivalent to the electron density) using a simplified stagnation point probe theory. As stagnation point probe theory is not too well understood, attempts were made at calibrating this device using free molecule probes and spectroscopic measurements. Some uncertainties still exist, however, and the absolute level of the free stream electron density is somewhat in doubt. Probably the electron density is known only within a factor of 1.5, but the relative density levels from one plasma condition to another are felt to be quite good.

The results of the measurements can best be interpreted using the one-dimensional electron energy equation with only those terms describing energy content storage, the pressure work term, and thermal conduction. The other terms that normally would appear in the equation, including the energy transfer term between ions and electrons, have been estimated and are thought small by comparison for the existing plasma conditions. Therefore (with no net current flow)

$$\frac{3}{2} n u k \frac{dT}{dx} + \frac{n u k T}{u} \frac{du}{dx} - \frac{d}{dx} K \frac{dT}{dx} = 0$$

where

- n = number density of the electrons
- u = velocity of the electrons
- k = Boltzmann constant
- T = electron temperature
- K = electron gas thermal conductivity.

In examining the region ahead of the atom shock wave, probe measurements showed that the electron density was constant. For the approximation of one-dimensional flow, nu is constant and u must therefore be constant as well. Hence in the free stream region ahead of the shock the pressure work term is zero. A simple differential equation describing a balance between heat diffusion and forced convection remains. Integrating once with the temperature gradient assumed to be zero far upstream of the atom shock gives

$$\frac{3}{2} n u k (T - T_\infty) = K \frac{dT}{dx}$$

where ∞ means conditions far from the shock. If the electron thermal conductivity were constant, a familiar exponential relationship would exist between T and x having a thermal diffusion length scale L of

$$L = \frac{K}{\frac{3}{2} nuk}$$

However, the electron thermal conductivity is a strong function of T and no simple integration is possible. Using the result of the first integration and the experimental measurements of T vs x as well as nu , the equation may be solved for the electron thermal conductivity at the shock location. The results of measurements for thermal conductivity of the electron gas are shown in Fig. 2 vs electron temperature. The conductivity has been nondimensionalized using the theoretical results of Spitzer[2] and the normalized results show no temperature dependence (note that in this experiment the collision frequency of the electrons with charged particles to that with neutral ones is one hundred to one so that fully ionized gas theory with current set equal to zero is appropriate). Within the scatter of the results, thermal conductivity is well described by a $T^{5/2}$ temperature dependence. The results are lower than Spitzer's by a factor of two. This measurement of K is unusual in using a known field to set up a steady state temperature distribution in the electron gas, and permits determination of the conductivity over a wide range of plasma properties.

The nondimensional temperature change associated with the flow through the atom shock is shown in Fig. 3. The temperature difference in the electron gas is shown to have a nearly linear variation with $T_{\epsilon}^{-5/2}$. At high temperatures $\Delta T/T_{\epsilon}$ approaches zero while at low temperatures there is a departure from the linear dependence on $T_{\epsilon}^{-5/2}$. At the low temperatures used in the experiment it is seen that the temperature increases as much as 33% over its value immediately ahead of the atom shock. The temperature increases across the shock wave because the electrons are compressed $(du/dx \neq 0$ here$)$, as are the neutrals. The temperature change in the limit of no thermal losses would be the isentropic value given by

$$\frac{T_s - T_\epsilon}{T_\epsilon} = \left(\frac{n_s}{n_\epsilon}\right)^{2/3} - 1 = 1.3$$

where ϵ, s are conditions immediately upstream and downstream of the shock wave, respectively.

However, thermal conduction reduces the isentropic value of $\Delta T/T_{\epsilon}$. In the limit of high temperatures or small changes in the electron temperature across the shock, it can be shown on theoretical grounds that a linear dependence on $T_{\epsilon}^{-5/2}$ for $\Delta T/T_{\epsilon}$ is to be expected for certain plasma conditions only. Of course, the heat loss in the shock wave compression of the electrons appears as the energy necessary to preheat the electrons upstream of the atom shock indicated in the previous paragraphs.

References

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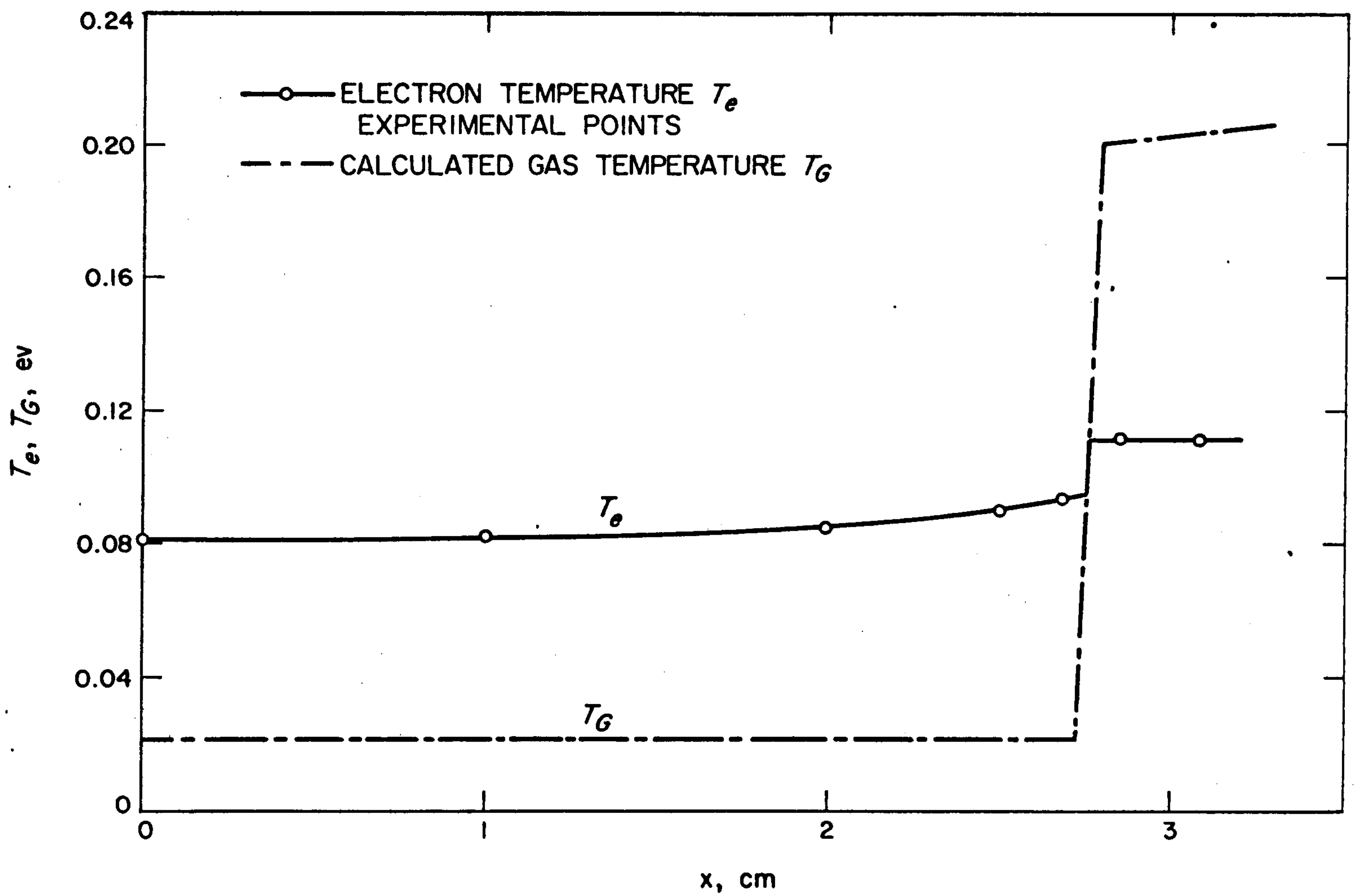
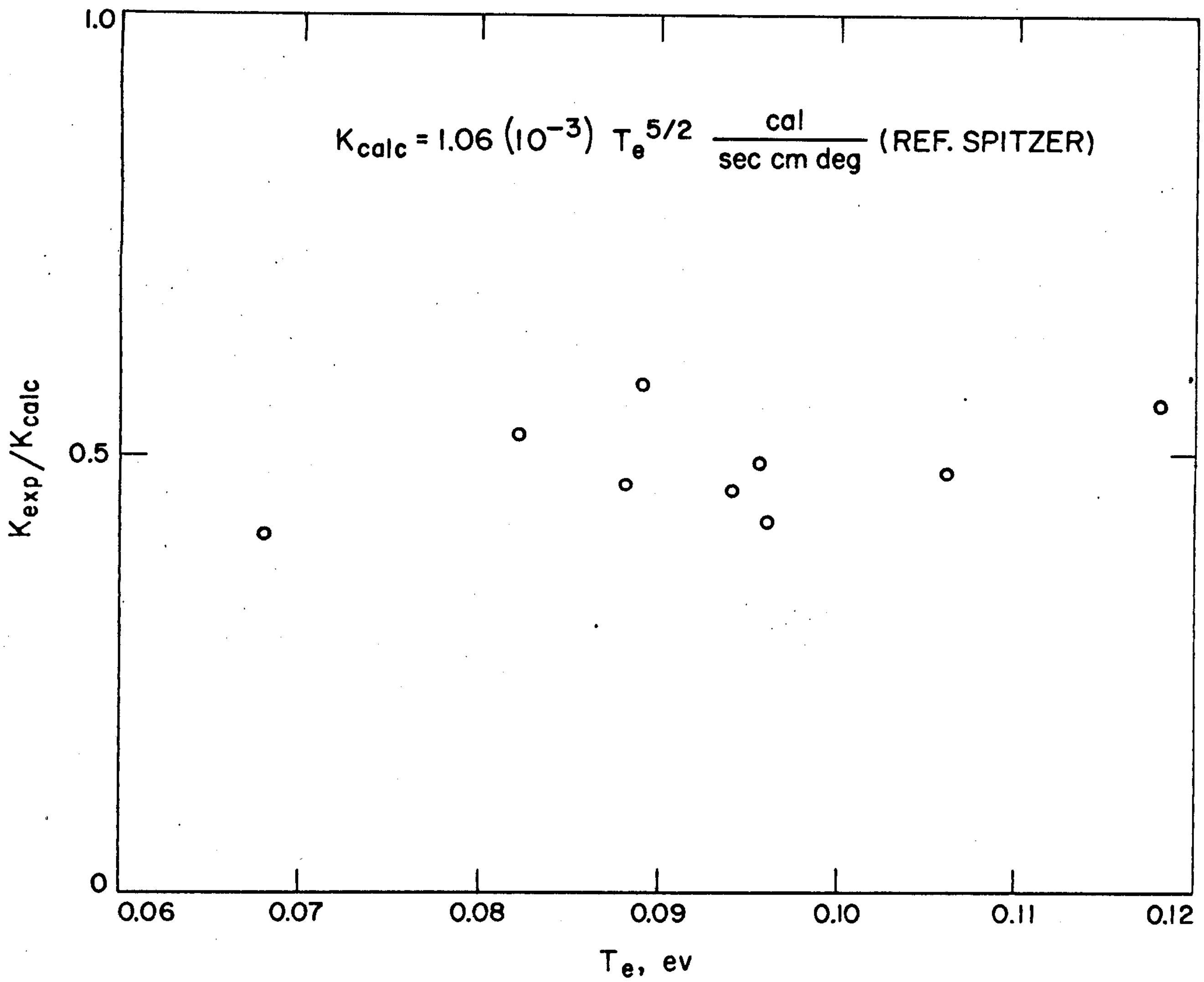
2. L. Spitzer, Jr., "Physics of Fully Ionized Gases," Interscience Tracts on Physics and Astronomy, Interscience Publishers, Inc , New York, 1956.



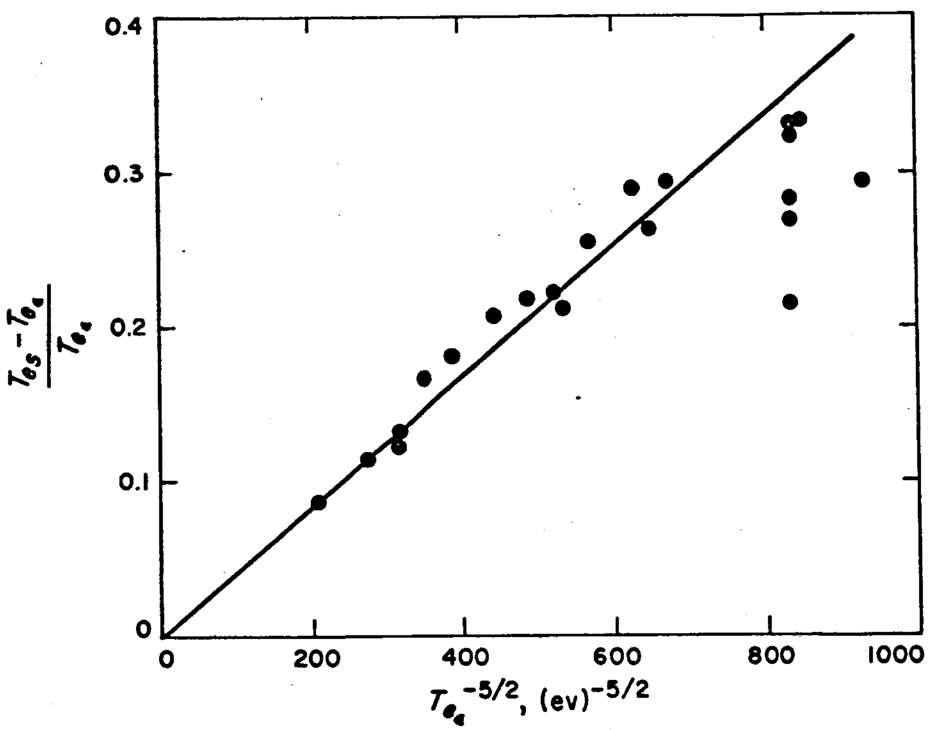
TYPICAL ELECTRON AND GAS TEMPERATURE PROFILES THROUGH SHOCK WAVE

Fig. 1



EXPERIMENTAL VALUES OF NORMALIZED
ELECTRON THERMAL CONDUCTIVITY
vs TEMPERATURE

Fig. 2



RATIO OF ELECTRON TEMPERATURE JUMP ACROSS SHOCK WAVE TO INITIAL TEMPERATURE vs THE RECIPROCAL OF THE INITIAL TEMPERATURE RAISED TO THE 5/2 POWER

Fig. 3